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2x2 MIMO-OFDM Gigabit fiber-wireless access system based on polarization division multiplexed WDM-PON

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Abstract: We propose a spectral efficient radio over wavelength division multiplexed passive optical network (WDM-PON) system by combining optical polarization division multiplexing (PDM) and wireless multiple input multiple output (MIMO) spatial multiplexing techniques. In our experiment, a training-based zero forcing (ZF) channel estimation algorithm is designed to compensate the polarization rotation and wireless multipath fading. A 797 Mb/s net data rate QPSK-OFDM signal with error free ($<1 \times 10^{-5}$) performance and a 1.59 Gb/s net data rate 16QAM-OFDM signal with BER performance of 1.2×10^{-2} are achieved after transmission of 22.8 km single mode fiber followed by 3 m and 1 m air distances, respectively.

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1. Introduction

Recently, known as 'home base station', femtocell network has been attracting more and more attentions due to its improved indoor coverage, increased capacity and reliable communication compared to macrocell network [1]. Radio-over-fiber (RoF) is considered as a promising candidate technology for femtocell networks because it allows for centralization of signal processing and network management, resulting in simple remote antenna unit (RAU) design and therefore low-cost implementation [2]. However, to meet the ever growing demand for high capacity wireless services like video-on-demand and video conferencing, it is highly desirable to develop new technologies for in-building femtocell networks. Wavelength division multiplexed passive optical network (WDM-PON) technology is therefore widely adopted to increase the capacity of RoF networks and the number of base stations serviced by a single central station [3], and the schematic scenario of in-home and in-building femtocell network is shown in Fig. 1. Moreover, to further increase the capacity per-wavelength of the femtocell network system, high spectral efficiency modulation and transmission technologies are highly desired. For instance, optical polarization division multiplexing (PDM) technology [4, 5] is regarded as an appealing solution by transmitting data in two orthogonal polarization modes within the same spectral range. Likewise, wireless multiple-input multiple-output (MIMO) technology is also a promising technology to exploit the spatial dimension by applying multiple antennas at both the transmitter and receiver sides [6].

Due to the inherent high chromatic dispersion tolerance in optical fibers and robustness against frequency selective fading or narrowband interference in wireless channels, orthogonal frequency division multiplexing (OFDM) has been widely used in current RoF systems [7]. Therefore, a RoF system combining OFDM with PDM and MIMO techniques can fulfill requirements of robustness, high flexibility and high spectral efficiency for providing broadband services in femtocell network. In addition, for multi-carrier systems like OFDM, a large computational complexity will be introduced by using the classical MIMO channel estimation method. In contrast, training-based channel estimation has the relatively low computational complexity at the receiver and draws more interests [8].

To date, some work has presented the concept of MIMO RoF system, but implemented separate fibers for each RAU [9]. A 397 Mb/s 16-quadrature amplitude modulation (QAM) OFDM-MIMO signal over WDM-PON system has been demonstrated in [10, 11] using different wavelengths instead of PDM technique for two transmitter antennas. 5 Gb/s PDM wireless MIMO transmission over 60 GHz wireless link has also been reported in [12], however, employing on-off keying (OOK) modulation. Moreover, some high speed PDM-OFDM transmission systems have been realized in [13, 14] without wireless transmission.

In this paper, we demonstrate a 2x2 MIMO-OFDM radio over WDM-PON system based on polarization division multiplexing and wireless MIMO techniques. The MIMO-OFDM training-based zero forcing (ZF) channel estimation algorithm is designed to compensate the optical polarization rotation and the wireless multipath fading. Furthermore, up to 1.59 Gb/s 16-QAM MIMO-OFDM fiber-wireless transmission over 1 m air distance and 22.8 km single mode fiber (SMF) are achieved for broadband wireless services around Gb/s. We also demonstrate the scalability of the proposed system under different signal to noise ratio (SNR), cross channel interference and wireless coverage by changing the wireless distance in our experiment.

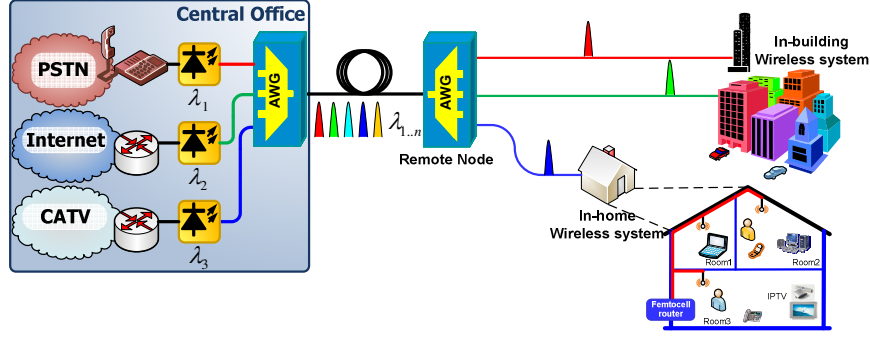


Fig. 1. The schematic scenario of in-home and in-building femtocell network system.

2. Training-based PDM-MIMO-OFDM composite channel estimation

Channel estimation is important for signal demodulation in MIMO system, in particular when a large number of subcarriers and advanced multiplexing technique are employed. In our PDM MIMO-OFDM system, the two orthogonal polarization modes which carry independent OFDM signal will experience a slow polarization rotation, which can be described as:

$$\begin{bmatrix} r_x \\ r_y \end{bmatrix} = H_F \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} t_x \\ t_y \end{bmatrix}, \quad (1)$$

where t_x and r_x are respectively transmitted and received X branch optical signals, so as t_y and r_y for Y branch signals. The symbol θ is the rotational angle. H_F represents the combined effect of fiber chromatic dispersion and polarization dependent loss. In our transmitter, after two photodetectors, two antennas are used to radiate two radio signals, respectively. The wireless channel response could be represented by a matrix H_{MIMO} . Notice that, the polarization rotation in fiber does not change so fast compared to the wireless channel, so it is not difficult to estimate the channel. The hybrid optical and wireless response for our MIMO-OFDM signal can be represented as Eq. (2), where n_x and n_y are the random noises, and h_{xx} , h_{xy} , h_{yx} and h_{yy} represent the elements in the combined channel response matrix.

$$\begin{bmatrix} r_x \\ r_y \end{bmatrix} = H_{MIMO} H_F \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} t_x \\ t_y \end{bmatrix} + \begin{bmatrix} n_x \\ n_y \end{bmatrix} = \begin{bmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{bmatrix} \begin{bmatrix} t_x \\ t_y \end{bmatrix} + \begin{bmatrix} n_x \\ n_y \end{bmatrix}. \quad (2)$$

In order to estimate this composite channel transfer matrix at the receiver, we transmit a pair of time-interleaved training sequences $T_X = [T_1, 0]^T$, $T_Y = [0, T_2]^T$ in the two tributaries. The received training sequences in two consecutive training durations can be expressed as:

$$\begin{bmatrix} RT_{x1} & RT_{x2} \\ RT_{y1} & RT_{y2} \end{bmatrix} = \begin{bmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{bmatrix} \begin{bmatrix} T_1 & 0 \\ 0 & T_2 \end{bmatrix} + \begin{bmatrix} n_{x1} & n_{x2} \\ n_{y1} & n_{y2} \end{bmatrix}, \quad (3)$$

where RT_{x1} and RT_{x2} stand for the received training symbol from X branch at the first and second training duration, respectively, so do RT_{y1} and RT_{y2} for the Y branch. And n_{x1} , n_{x2} , n_{y1} and n_{y2} are the random noises. The estimated channel transfer matrix then can be easily calculated as Eq. (4). From Eq. (4) we see that even with perfect channel estimation an error term will occur due to the random noises. More advanced algorithm such as minimum mean-squared-error (MMSE) algorithm could be used to improve the performance. However, in our experiment, zero forcing (ZF) instead of MMSE algorithm is used for channel estimation due to its lower computational complexity [4].

$$\begin{bmatrix} \tilde{h}_{xx} & \tilde{h}_{xy} \\ \tilde{h}_{yx} & \tilde{h}_{yy} \end{bmatrix} = \begin{bmatrix} RT_{x1}/T_1 & RT_{x2}/T_2 \\ RT_{y1}/T_1 & RT_{y2}/T_2 \end{bmatrix} = \begin{bmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{bmatrix} + \begin{bmatrix} n_{x1}/T_1 & n_{x2}/T_2 \\ n_{y1}/T_1 & n_{y2}/T_2 \end{bmatrix}. \quad (4)$$

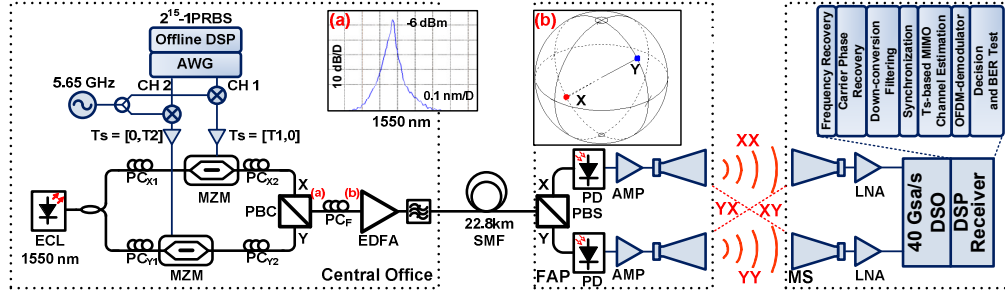


Fig. 2. Experimental setup for the proposed PDM MIMO-OFDM system.

3. Experimental setup

The experimental setup for a single wavelength channel of our proposed MIMO-OFDM signal over PDM WDM-PON system is shown in Fig. 2, for a demonstration purpose. At the central office (CO), a 1.25 GSa/s arbitrary waveform generator (AWG) is performed to generate two-channel baseband real-valued OFDM signals. For each channel, a data stream with a pseudo-random bit sequence (PRBS) length of $2^{15}-1$ is mapped onto 129 subcarriers, of which 64 subcarriers carry real QPSK/16-QAM data and one is unfilled DC subcarrier. The remaining 64 subcarriers are the complex conjugate of the aforementioned 64 subcarriers to enforce Hermitian symmetry in the input facet of 256-point inverse fast Fourier transform (IFFT). The cyclic prefix is 1/10 of the IFFT length resulting in an OFDM symbol size of 281. To facilitate time synchronization and MIMO channel estimation, 3 training symbols are inserted at the beginning of each OFDM frame that contains 7 data symbols. Each channel has a net data rate of 398.5 Mb/s ($1.25 \text{ GSa/s} \times 2 \times 64/281 \times 7/10$) for QPSK case and 797.1 Mb/s for 16QAM case with a bandwidth of 629.8 MHz ($1.25 \text{ GSa/s} \times 129/256$). For simplicity, one frame delay is applied in one channel to decorrelate the two channel signals in the AWG. These two-channel OFDM signals are then separately up-converted to 5.65 GHz. The two RF OFDM signals are used to modulate a 100 kHz-linewidth continuous-wave (CW) external cavity laser (ECL, $\lambda_1 = 1550 \text{ nm}$) at two Mach-Zehnder modulators (MZMs), respectively. A pair of polarization controllers (PCs), namely PC_{X1} and PC_{Y1} are used to optimize the response of the MZMs. PC_{X2} and PC_{Y2} are inserted at the MZMs outputs to align the optical OFDM signal in each channel to the X and Y axis of the following polarization beam combiner (PBC), which then combines the two orthogonal polarizations. Subsequently PC_F is introduced to roughly adjust the polarization of optical signal in the trunk fiber and set the variable power splitting ratio for equal SNR at each transmitter antenna. An erbium-doped fiber amplifier (EDFA) and an optical filter with 0.8 nm bandwidth are used to boost the optical OFDM signal and filter out the outband noise. The optical spectrum and the poincaré sphere of the combined optical signal are shown in the insets of Fig. 2. After excluding the overhead from cyclic prefix and training sequences, the output signal from the PBC is at a net data rate of 797 Mb/s with a spectral efficiency of 1.26 bits/s/Hz for QPSK case and 1.59 Gb/s with a spectral efficiency of 2.52 bits/s/Hz for 16-QAM case.

After 22.8 km of standard single mode fiber (SSMF) propagation, the optical OFDM signal is divided back to X and Y polarizations by a polarization beam splitter (PBS) at the femtocell access point (FAP). By using two 10 GHz bandwidth photodiode (PD), these two tributaries are converted into the RF signals, which are then fed into the FAP antennas after two RF amplifiers with 20 dB gain. After air transmission, these two wireless signals are detected by two receiver antennas and amplified by two 20 dB gain low-noise amplifiers

(LNAs) at the mobile station (MS) receiver. Subsequently, a 40 GSa/s digital sampling oscilloscope (DSO) with 13 GHz analog bandwidth is used to capture these two RF signals. Offline signal demodulation is then performed by a digital signal processing (DSP)-based receiver consisting of frequency and phase recovery, frequency down-conversion, training-based PDM MIMO-OFDM channel estimation, OFDM demodulation modules, data mapping and bit error rate (BER) tester. In our experiment, 80896 bits are calculated for BER test.

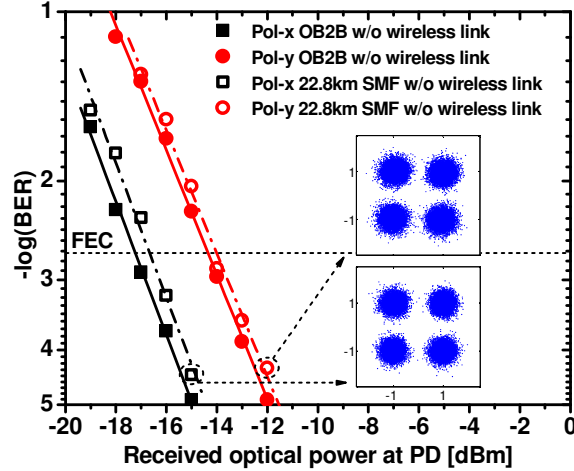


Fig. 3. Measured BER performance of Pol-x and Pol-y signal in optical B2B case and 22.8 km SMF fiber transmission case.

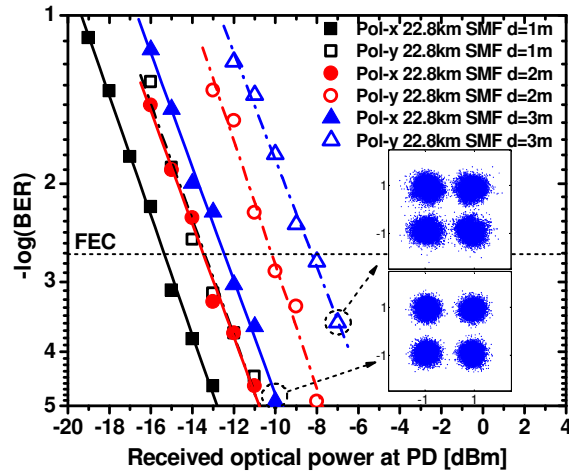


Fig. 4. Measured BER performance of PDM MIMO-OFDM signal wireless transmission with 22.8 km SMF fiber transmission.

4. Experimental results and discussions

Figure 3 shows the measured BER in terms of the receiver optical power into the PD in both optical back to back (OB2B) and 22.8 km SMF transmission cases without wireless link. In optical B2B case, we can observe that the receiver sensitivity at the forward-error correction (FEC) limit (BER of 2×10^{-3}) is achieved at -17.2 dBm and -14.3 dBm for the X polarization OFDM signal (Pol-x) and Y polarization OFDM signal (Pol-y), respectively. This 2.9 dB power penalty between Pol-x and Pol-y could be attributed to the different performances of optical and electrical components, particularly the responsivity of the two

photodiodes used in these two branches. Negligible power penalty (around 0.5 dB) is induced after 22.8 km SMF transmission by using training-based MIMO OFDM channel estimation algorithm. The received constellations of Pol-x and Pol-y signal after 22.8 km SMF transmission are shown in the insets of Fig. 3 as well.

Figure 4 presents the wireless transmission BER performance of QPSK-OFDM PDM-MIMO signal after 22.8 km SMF transmission. The separation spacing between the elements of the FAP and MS antenna arrays is fixed at 1 m in the experiment. The received sensitivity at the FEC limit is obtained at -15.2 dBm, -13.4 dBm and -12.5 dBm for the Pol-x signal over air transmission of 1 m, 2 m and 3 m, respectively. The higher required optical power at the FEC limit as air distance increases can be attributed to the increasing cross interference, severer multipath effect and lower SNR. We can also note that larger power penalty is induced between Pol-x and Pol-y for longer air distance. This could be explained by the misalignment between the transmitter and receiver antennas. The received constellations of Pol-x and Pol-y with 3 m air distance and 22.8 km SMF transmission are indicated in the insets of Fig. 4.

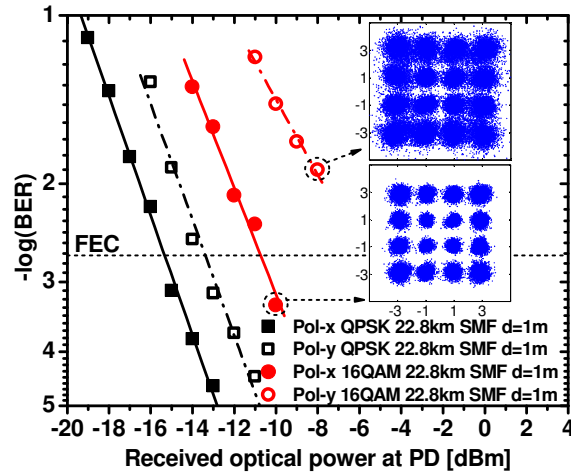


Fig. 5. Measured BER performance of 797 Mb/s QPSK MIMO-OFDM and 1.59 Gb/s 16-QAM MIMO-OFDM signal over 1 m air distance and 22.8 km SMF transmission.

We also test the performance of 1.59 Gb/s 16-QAM MIMO-OFDM signal over 1 m air distance and 22.8 km SMF transmission, as depicted in Fig. 5. We can see that the receiver sensitivity of 16-QAM MIMO-OFDM Pol-x signal to reach the FEC limit is -10.7 dBm. 4.5 dB power penalty compared to QPSK MIMO-OFDM Pol-x wireless transmission can be explained that the constellations states of higher-level modulation format are closer than QPSK, resulting in higher SNR requirement for the same performance. The received constellations of 16-QAM MIMO-OFDM signal are shown in the insets of Fig. 5. The constellation symbols at the higher amplitude are dispersed widely compared to the center ones. This is expected, since OFDM signal is sensitive to the nonlinearity of fiber and wireless transmission due to its high peak-to-average-power-ratio (PAPR). However, we can get BER of 5.01×10^{-4} and 1.28×10^{-2} for 16-QAM MIMO-OFDM Pol-x and Pol-y signal after 1 m air distance and 22.8 km SMF transmission, respectively.

5. Conclusion

We have presented a spectral efficient and WDM-PON compatible MIMO-OFDM access system by combining optical polarization division multiplexing (PDM) and wireless multiple input multiple output (MIMO) spatial multiplexing techniques. Moreover, a training-based zero forcing (ZF) scheme is digitally developed to estimate the polarization multiplexed MIMO transmission channel. A 797 Mb/s net data rate QPSK-OFDM signal and a 1.59 Gb/s

net data rate 16 QAM-OFDM signal at 5.65 GHz RF carrier frequency are transmitted over 3 m and 1 m air distance with 22.8 km single mode fiber, respectively. This system has potential application in future in-door femtocell network supporting Gb/s broadband wireless service.

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